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Present Status and Perspectives of Long Wavelength Free Electron Lasers at Kyoto University

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Abstract

A mid-infrared Free Electron Laser (FEL) named as Kyoto University FEL (KU-FEL) has been developed for energy-related research at Institute of Advanced Energy, Kyoto University. The wavelength range of KU-FEL is 3.6 - 23 μm and opened for various user experiments. A compact THz-FEL, which consists of a photocathode RF gun, a bunch compressor, and an undulator, is now under construction. Present status and perspective of the FEL facility at Kyoto University is reported in this paper.

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Keywords: Mid-infrared free electron laser; THz free electron laser

1. Introduction

Free Electron Laser (FEL) is the coherent light source which has very wide tunability of wavelength. In the long wavelength region such as mid-infrared (MIR) and far-infrared (FIR), FELs are recognized as one of the most intense lasers having very wide tunability of wavelength. At Institute of Advanced Energy, Kyoto University, an MIR-FEL named as Kyoto University Free Electron Laser (KU-FEL) has been developed for promoting the energy-related research (Zen et al. (2008)). A compact THz-FEL is now under development. The schematic diagram of the long wavelength FEL facility at Kyoto University is shown in Fig. 1.

The KU-FEL achieved its first lasing in 2008 (Ohgaki et al. (2008)). After the first lasing, we continuously made efforts to improve the FEL performance, i.e. wavelength range, and intensity. The undulator and optical cavity mirrors were replaced in 2013. Thanks to those replacements, the tunable range of the KU-FEL has been extended

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from 11-14 µm to 5 to 22 µm (Zen et al. (2013)). In parallel to those efforts, instruments for stabilizing the electron beam position and energy were developed to increase the stability of FEL wavelength and intensity. Six non-destructive beam position monitors and feedback control system based on measured beam position were developed (Ohgaki et al. (2013) and Zen et al. (2014)). The long-term stability of power and wavelength of KU-FEL has been drastically improved by using the developed feedback control system. The KU-FEL performance was again checked in June 2016. We found that the FEL can supply laser beam with sufficiently high macro-pulse energy in the wavelength range from 3.6 to 23 µm. The application experiments using KU-FEL was started in 2009. The KU-FEL is now opened to internal and external users. For user experiments, an MIR beam transport line which covered by plastic tubes was constructed and evaluated (Yoshida et al. (2013)). Three user stations (US#1, #2, and #3 in Fig. 1) are available for various user experiments. The user station #1 is the station for simple irradiation and FEL beam diagnostics. Focusing optics for irradiation and a monochromator for FEL wavelength measurement are available in this station. The user station #2 is the station for pump-probe experiments. A picosecond near infrared, visible, and UV lasers synchronized with MIR-FEL micro-pulse is available at this station. A Q-switching ns-Nd:YAG laser synchronized with MIR-FEL macro-pulse is also available at this station. The user station #3 is for multi-purpose usage. There is an optical table at the station #3. Users can bring and construct their own experiment apparatus to this station. Present status of KU-FEL is described in this paper.

Research work on the compact THz-FEL facility was started in 2008. Construction of the THz-FEL was started in 2012. The first photoelectron beam was observed in May 2015. The electron beam property measurement was already done and reported in Damminsek et al. (2015) and Suphakul et al. (2016). An undulator will be installed in summer of 2016 and first light will be measured. The development status of the THz-FEL is reported in this paper.

Since the development of MIR-FEL is almost done. We are now considering an upgrade of the facility. Our current upgrade plan of the facility is also reported in this paper.

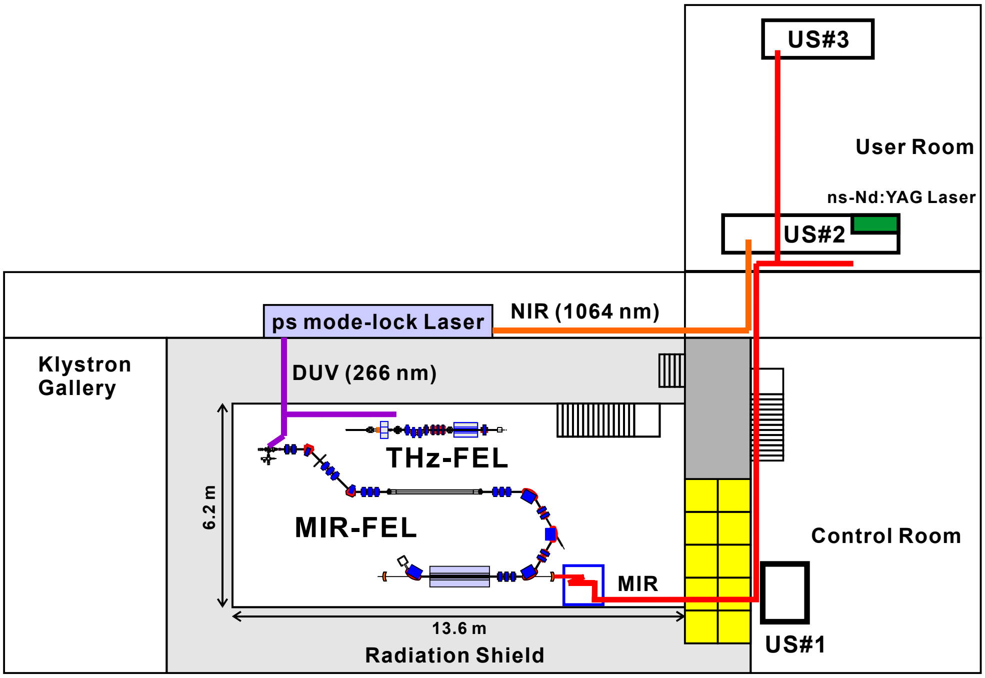

Fig. 1. The schematic diagram of long wavelength FEL facility at Institute of Advanced Energy, Kyoto University in July 2016. US#1 indicates the user station for MIR-FEL beam diagnostics and simple irradiation experiments. US#2 indicates the user station for pump-prove experiments. US#3 indicates the user station where users can bring their equipment. A picosecond mode-locked laser synchronized with the FEL driving electron accelerators can be used for driving photocathode in the accelerator and for a pump or prove light of pump-prove experiments. The transport line of MIR-FEL is covered by plastic tubes and the inside of the tube can be filled with nitrogen gas in order to avoid absorption of MIR laser light by CO_2 and H_2O molecules in the air.

2. Present Status of Mid-Infrared FEL at Kyoto University

A mid-infrared oscillator FEL named as KU-FEL has been developed for energy-related research at Institute of Advanced Energy, Kyoto University. The schematic diagram of KU-FEL is shown in Fig. 2. The FEL oscillator consists of a 4.5-cell thermionic RF gun, an energy filtering dog-leg section, 3-m traveling wave accelerator tube, a bunch compression 180-degree arc section, a 1.8-m undulator, and an optical resonator. Main parameters of each component were reported in Zen et al. (2013). Although the initial target wavelength range of the FEL was 5 to 20 μm, the FEL can be oscillated in the wavelength range from 3.6 to 23 μm. The typical performance of KU-FEL which was confirmed in June 2016 is summarized in Table 1. The available FEL macro-pulse energy measured by a calibrated pyroelectric detector (818E-20-50S with multi-function optical meter 1835-C, Newport) at the user station #1 without nitrogen gas filling to the transport line is shown in Fig. 3 (a). The FEL spectra measured by a monochromator (Digikrom 240, CVI) and a pyroelectric detector (QE8SP-I-BL-BNC, Gentec-EO) are shown in Fig. 3 (b). Since the spectrum measurement setup is not good for measuring the spectrum of 23 μm laser beam, the central wavelength was determined by measuring the spectrum of third harmonics of the fundamental oscillating wavelength, which is inherently generated when an oscillator FEL oscillates.

The cathode used in the RF gun is made of single crystal of Lanthanum hexaboride. It was known that the cathode can be also operated as a photocathode (for example, reported in Boussoukaya et al. (1988)). We have developed a multi-bunch UV laser (Zen et al. (2015)) and a performance test of the facility under the photocathode operation was conducted at the FEL wavelength of 11.8 μm. The results were reported in Zen et al. (2016). Under the photocathode operation, the micro-pulse energy of the FEL was increased from 2 to 13 μJ. It was demonstrated that the photocathode operation enabled us to increase the micro-pulse energy of the KU-FEL.

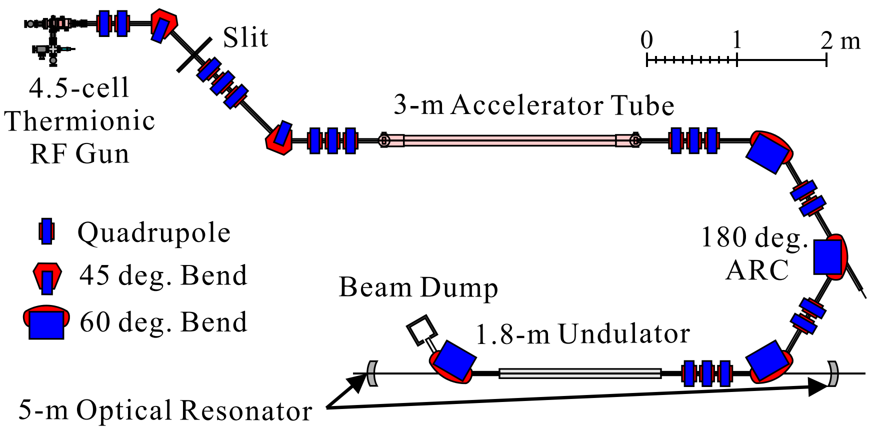

Fig. 2. Schematic diagram of KU-FEL, mid-infrared free electron laser at Institute of Advanced Energy, Kyoto University.

Table 1. The typical performance of KU-FEL in July 2016.

Wavelength range	3.6 – 23 μm
Spectrum width	~ 3%
Macro-pulse repetition rate	1 – 2 Hz
Maximum macro-pulse energy	30 mJ @5 μm
Macro-pulse duration	~ 2 μs
Micro-pulse repetition rate	2856 MHz
Maximum micro-pulse energy	~ 5 μJ @5 μm
Micro-pulse duration	0.6 ps @12 μm (Qin et al. (2012))

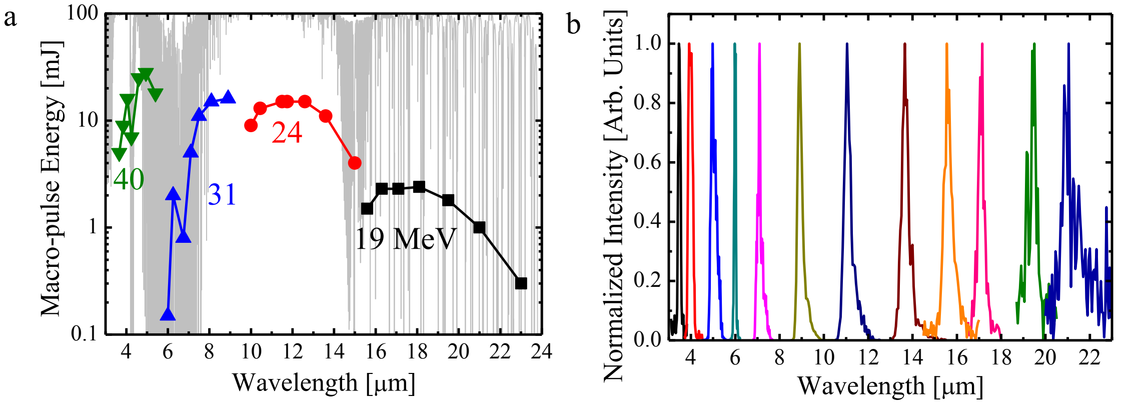

Fig. 3. (a) The available macro-pulse energy of KU-FEL at the user station #1 (shown in Fig. 1) without filling nitrogen gas to the transport line; (b) The normalized wavelength spectrum of KU-FEL measured at user station #1 (shown in Fig. 1). The gray line in (a) is the percent transmission of the air calculated by HITRAN (Reference: Hitran on the web) to show the influence of absorption in the air. The value written in (a) is the electron beam energy. Under the same electron beam energy condition, the wavelength was varied by changing the magnetic field strength of the undulator.

3. Development Status of THz-FEL at Kyoto University

A compact THz-FEL is under construction at Institute of Advanced Energy, Kyoto University. The schematic diagram of the THz-FEL is shown in Fig. 4. The THz-FEL consists of a 1.6-cell photocathode RF gun, a focusing solenoid, UV-laser injection chamber, a bunch compression chicane, a triplet quadrupole, and an undulator. The RF gun has no laser injection port in the cathode cell. The UV-laser was injected from the electron extraction port through the UV-laser injection chamber. The photograph of the present setup of the compact THz-FEL is shown in Fig. 5. The undulator has not been installed yet but the electron beam property measurements have already been done. The detailed measurement results were reported in Damminsek et al. (2015). The measurement results are summarized in Table 2. In order to check the bunch compression system, an aluminum foil was inserted in the beamline and the coherent transition radiation (CTR) was generated by injecting the electron bunch to the foil. The intensity dependence of CTR on the laser injection phase and the excitation current of the chicane bunch compressor have already been measured by using focusing optics and a pyroelectric detector (PYD-1-018, PHLUXi). As the result, the clear CTR intensity dependence on the laser injection phase was observed. Detail of experiment setup and results were reported in Suphakul et al. (2016). The frequency spectrum of the CTR was measured by using a Michelson interferometer and the PYD-1-018 pyroelectric detector. The highest frequency detected was 0.25 THz.

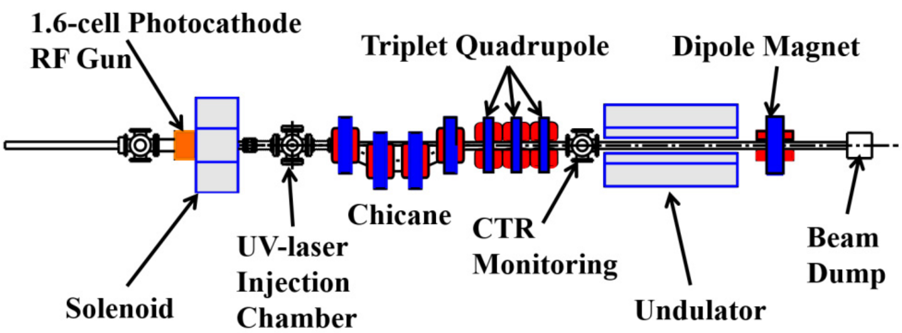

Fig. 4. Schematic diagram of THz-FEL at Institute of Advanced Energy, Kyoto University.

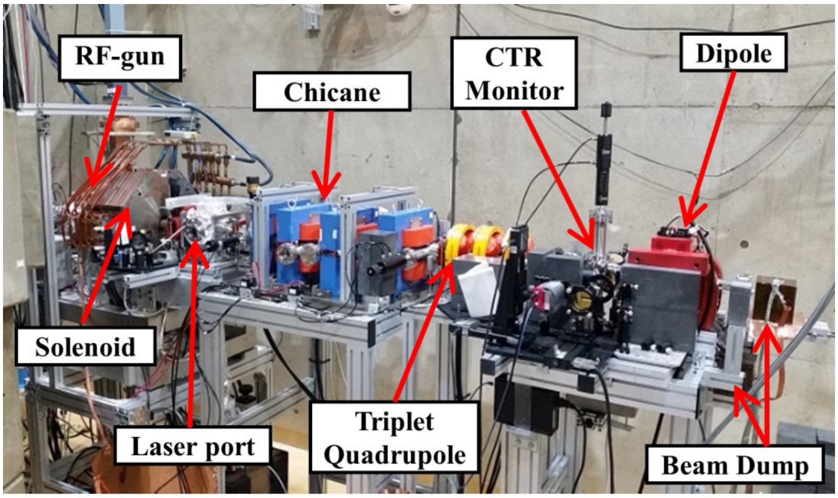

Fig. 5. Photograph of the present setup of the compact THz-FEL. The undulator has not been installed yet.

Table 2. Summary of measured electron beam property obtained in THz-FEL.

Electron beam energy	4.6 MeV
Relative RMS energy spread	1.3%
Maximum bunch charge	1.4 nC
Minimum normalized transverse emittance (measured at the bunch charge of 50 pC)	Horizontal : 6 π mm-mrad Vertical : 8 π mm-mrad

A planer Halbach type undulator which has the period length of 70 mm and 10 periods has already been prepared for the THz-FEL. The magnetic field of the undulator has already been measured. The measured K-value dependence on the undulator gap is shown in Fig. 6. The maximum K-value is 2.81 at the undulator gap of 30 mm. From the electron beam energy (4.6 MeV), period length of the undulator (70 mm), and the maximum K-value of the undulator (2.81), the lowest resonant frequency is calculated as 184 GHz. The lowest resonant frequency is lower than the highest frequency of the CTR. Therefore, generation of coherent undulator radiation at 200 GHz can be expected when the undulator is installed. The installation of the undulator is now scheduled in summer of 2016 and the first coherent undulator radiation from this system will be measured.

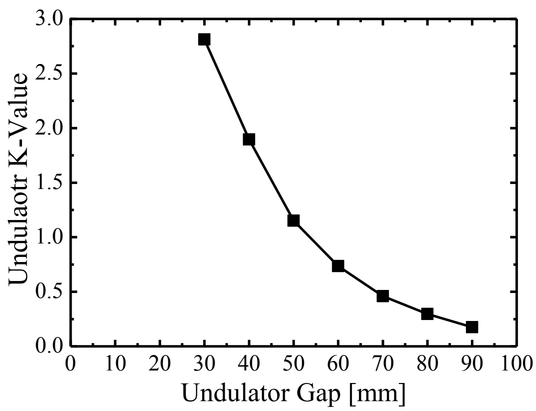

Fig. 6. The K-value dependence of the THz- FEL undulator on the undulator gap.

4. Future Perspective of Long Wavelength FEL facility at Kyoto University

Since the development of MIR-FEL is almost finished, upgrade project of the facility is under discussion. The possible arrangement of additional beamlines added to the MIR-FEL is shown in Fig. 7. As shown in the figure, in the accelerator room, we still have a space to extend one FEL branch and two non-FEL branches. The second FEL branch will be used for far infrared (FIR) FEL generation. The target wavelength of this FIR-FEL branch has not been fixed yet. We need to have deep discussions with users who interested in the applications of intense FIR tunable laser for determining the target wavelength. We also need to make careful investigation about the available wavelength range with existing electron linac. One of the two non-FEL branches will be used for coherent THz radiation generation. In the branch, compressed multi-bunch electron beam with more than 10000 bunches can be easily used. Therefore, CTR from a metallic foil (Happekk et al. (1991) and Shibata, et al., (1992)), Vavilov-Cherenkov radiation from a grating pair (Smirnov, et al. (2015)), and resonant coherent diffraction radiation (Honda et al. (2014)) can be generated. And the branch can be used for demonstration of various novel coherent THz generation schemes using a high-quality multi-bunch electron beam. The other non-FEL branch can be used for electron beam irradiation and other interesting applications.

The coherent edge radiation at the bending magnet located at the downstream of the 1.8-m undulator was measured to check the feasibility of short bunch electron beam generation by the existing 40-MeV linac which usually used for driving the MIR-FEL. The schematic diagram of the measurement setup and measured spectrum are shown in Fig. 8 (a) and (b), respectively. The measured spectrum clearly contains frequency component up to 2.0 THz. From this result, we can conclude that the THz generation branch is feasible. For the FIR-FEL branch, whether FEL oscillation at the THz region is possible or not is unclear. However, at least, we can generate the coherent undulator radiation in the THz region.

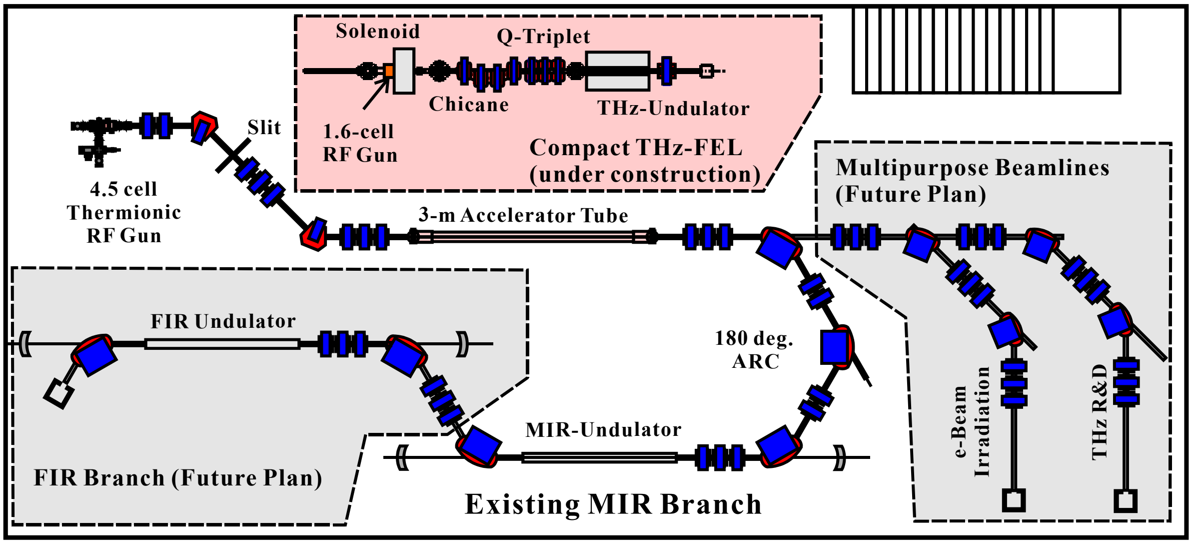

Fig. 7. The possible arrangement of additional beamlines added to the MIR-FEL.

Acknowledgements

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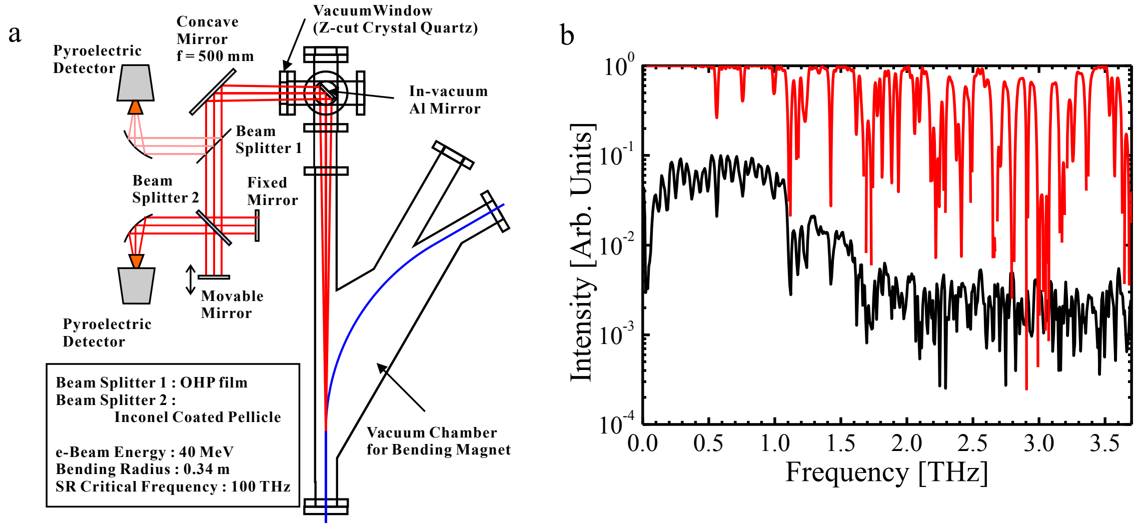

Fig. 8. (a) Measurement setup of coherent edge radiation from the bending magnet located at the downstream of the 1.8-m undulator. The blue line indicates the electron trajectory. The red lines indicate the optical path of the coherent edge radiation; (b) The measured coherent edge radiation spectrum (black line) and the expected transmission spectrum of the air in the measurement setup calculated by HITRAN (red line).

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